Development of UAV Indoor Flight Technology for Building Equipment Works

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Abstract –

In the Japanese construction industry, An UAV has begun to be used for outdoor works. On the other hand, most of building equipment works is indoor work, often working in touch with the surrounding environment near the ceiling.

Air volume measurement is an example of building equipment works near the ceiling. Conventionally, a worker gets on a temporary scaffold to approach the ceiling at the high position and measures the air volume just under the diffuser installed on the ceiling with using the handy type anemometer. This conventional work has low productivity and high cost for safety management. Furthermore, this tendency is remarkable in rooms with high ceilings such as entrance halls and factories.

We propose a new measurement method using the UAV with air volume measuring device, and develop and evaluate the system. The visual feedback control system for self-localization is also developed because the GPS cannot be used indoors. In addition, a high ceiling room with the diffuser is constructed as a mock-up for experiment. We analysed the positioning errors of the UAV when hovering and when approaching and touching the diffuser. Also, we evaluated the touch performance of the UAV to the ceiling by measuring the air volume.

As a result, it was found that the UAV can ensure the performance necessary for air volume measurement in this experiment.

Keywords –

UAV; Indoor Flight Technology; Building equipment works; Air Volume Measurement

1 Introduction

In the Japanese construction industry, the number of young workers is decreasing and skilled workers are aging. For that reason, efforts to improve productivity such as "i-Construction" by using information technology (IT) and robot technology are under way. One of them is the UAV (Unmanned Aerial Vehicle). In civil engineering work, UAV are used for management of river facilities [1] and monitoring for bridge degradation [2]. In building work, quality is managed by using images taken from the sky [3]. However, there are no cases of using UAV in buildings under construction. The main cases are monitoring, confirmation, and three-dimensional measurement by cameras and others. There are no cases of working in touch with the surrounding environment or members such as transportation and installation. Building equipment works such as air conditioning, sanitation and electricity is mostly work in the building, especially in the vicinity of the ceiling using temporary scaffolding. In order to utilize UAV in building equipment works, it is necessary to perform self-positioning without GPS, to recognize the surrounding environment, and to make direct touch with the surrounding environment.

One of the tasks near the ceiling in building equipment works is air volume measurement. Air volume measurement is a task of checking whether the amount of conditioned air blown out from the diffuser provided on the ceiling surface of a room is in accordance with the design value, and in general, total measurement is required. Conventionally, wind speed distribution immediately below the diffuser is measured by a handy type anemometer, and air volume is calculated by multiplying the average value by the opening area. Although temporary scaffolds are necessary to approach the diffuser in a high place, work efficiency decreases due to assembly, movement and disassembly of temporary scaffolds. Furthermore, safety management is important because it is work in a high place. The authors developed a device to measure the amount of air passing through the hood by bringing the hood for collecting wind into close touch with the ceiling surface by an elevating mechanism [5]. As a result, the safety and productivity of the air volume measurement work have improved. However, since there is a limit to the height of the equipment, measurement using a temporary scaffold is required as in the past for diffuser in rooms with high ceilings such as entrance halls and factories. Also, if obstacles such as furniture and production equipment are installed right under the diffuser, it is difficult to install the scaffold. On the other hand, if it is possible to measure the air volume using UAV, it can be expected that the problem when the person measures the air volume using the temporary scaffold or air volume measuring device as described above is solved.

In this research, for the purpose of developing a UAV which can be used indoors in building equipment works, we developed a UAV capable of measuring air volume and evaluated its performance.

2 System Overview

2.1 System Configuration

The new system consists of UAV equipped with an "Air Volume Measurement Unit", and a vision system with camera and PC.

The UAV is an oct-copter shown in Figure 1. In order to mount the "Air Volume Measurement Unit" in the center of the UAV, the frame was arranged in parallel crosses. The flight controller and the battery were arranged in a dispersed manner in the frame. The "Air Volume Measurement Unit" (Figure 2) consists of a "Collect Wind Hood" for collecting air flow from the air inlet, a "Sensor Hood" with five wind speed sensors, and a control and communication circuit of the wind speed sensor and a battery. In addition, neoprene rubber was attached to the upper end of the "Collect Wind Hood" considering ease of adhesion with the ceiling surface. Furthermore, CFD (Computational Fluid Dynamics) was performed and the lower end of the sensor hood is set to be 90 mm lower than the propeller position, so that the airflow generated by the propeller did not influence the air flow measurement. Other specifications of the UAV, specifications of the camera and specifications of the wind speed sensor are shown in Table 1.

2.2 Estimation of Position and Attitude using Vision System

In this research, we decided to use a vision system (Figure 3) that recognizes markers attached to the UAV with cameras installed in the environment as a self-position estimation method for indoor UAV that cannot use GPS. There are various methods such as SLAM and inertial navigation as self-position estimation methods in an environment where GPS cannot be used. We thought that the vision system that recognizes markers on UAV with cameras installed in the environment has the following two merits, and we chose this in the present study.

1. Since the target position can be set on the camera image, it can be used, for example, when there is no 3D model in the existing building or when the 3D model does not conform to the current situation.

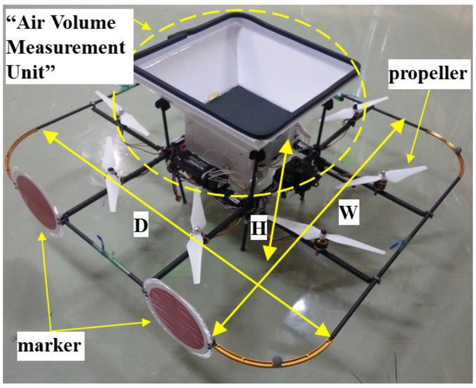

Figure 1. Appearance of UAV

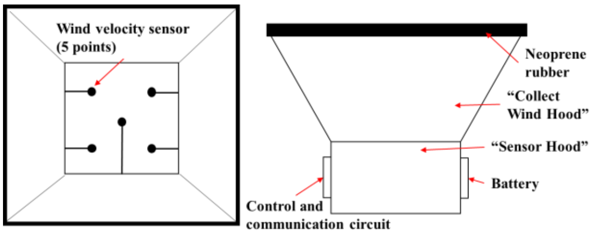

Figure 2. "Air Volume Measurement Unit"

Table 1. System specification

UAV	
Flight controller	Pixhawk
Size [mm]	D800 × W800 × H400
Frame material	Carbon fiber
Battery	Lithium polymer battery (2 pieces)
Propeller size [in]	9.45
Weight [kg]	2.5
Sensor	Accelerometer (3 axes), gyroscope (3 axes), barometer
Camera	
frame rate [fps]	30 (Max)
pixels	1920 × 1080
angle of view [°]	90
wind speed sensor	
Measurement method	Hot-wire
Measurement range	0.05～12.0m/s

2. Since the measurement is performed by the camera installed in the environment to be used, there is no need to install a sensor for recognizing the external environment in the UAV. As a result, the size of UAV can be minimized.

Next, we describe a method for estimating the position and attitude of UAV by recognizing markers. The markers on the UAV are two red circular marks (Figure 3). Two red circular marks are extracted from the image acquired by the camera and a circle is obtained with the line connecting the centers of the two circular marks as diameter, so as to find the area of the circle (A_m) and the position on the screen (X_m,Y_m). Based on the area of a circle (A_b) obtained from two circular marks arranged 3 m ahead (D_b) so as to face the camera and the actual distance (X_b,Y_b) to one pixel at 3 m ahead, the horizontal coordinate of the camera *(X)* is given by Equation (1), the vertical coordinate of the camera *(Y)* is given by Equation (2), and the depth coordinate of the camera *(Z)* is given by Equation (3). Also, from the size of the two markers recognized by the camera, determine the attitude of the UAV in the vertical axis rotation direction. The target position can be set by determining the position and area of the circle on the camera image.

$$X = X_b * X_m * \sqrt{A_b / A_m} \tag{1}$$

$$Y = Y_b * Y_m * \sqrt{A_b / A_m} \tag{2}$$

$$Z = \sqrt{{D_b}^2 * A_b / A_m} \tag{3}$$

2.3 Control of UAV

Position control of the UAV is performed as follows. The difference is obtained from the target position set on the camera image and the UAV position, and the PID control as shown in Equation (4) is performed so that the UAV position approaches the target position. In addition, when the deviation between the target coordinates and the position coordinates of the UAV becomes within the threshold value, it is automatically controlled so as to maintain the height by using the barometer. This was used as a safety measure to prevent the UAV from falling when the UAV became unmeasurable by the vision system.

Attitude control of the UAV is performed as follows. The control method differs between the rotation direction of the vertical axis and the two rotation directions of the horizontal axis. The rotation direction of the vertical axis performs PID control using the direction of UAV with respect to the camera, and rotates the UAV so as to face the camera. The control of the two rotation directions of the horizontal axis is performed automatically by the flight controller so that the UAV becomes horizontal.

$$u(t) = K_P e(t) + K_I \int e(\tau)dt + K_D \frac{d}{dt} e(t) \tag{4}$$

3 Evaluation Experiment

In order to evaluate the function and performance of the new UAV, we conducted a flight experiment. The experimental site was a simulated ceiling with a diffuser as shown in Figure 4. In addition, we used the motion capture system “OptiTrack” using an infrared camera to measure the flight path.

First, we evaluated the basic performance of the UAV by hovering. Furthermore, as the performance required for air volume measurement, the approach performance to the diffuser and the touch performance with respect to the ceiling were evaluated.

3.1 Hovering Performance

3.1.1 Experimental Method

For confirmation of hovering performance, a target was set in the air, hovering for 30 seconds, and the flight trajectory was measured. In order to eliminate the disturbance of flight caused by the UAV's own airflow

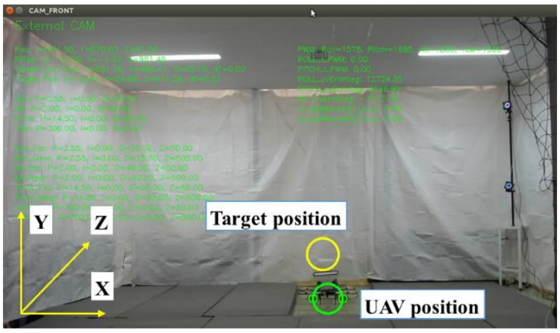

Figure 3. Overview of vision system

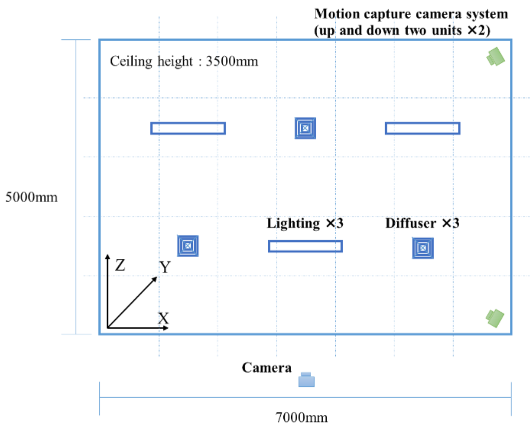

Figure 4. Experiment field (plan view)

during take-off, by passing the string through the center of the UAV, we restrained the UAV from moving in the horizontal direction. After the UAV reached the target, the string was loosened and hovering was performed.

3.1.2 Result

Figure 5 shows the hovering flight trajectory (5 flights). The vertical axis is the vertical direction of the camera (Y), the horizontal axis is the horizontal direction of the camera (X) in the left figure, and the depth direction of the camera (Z) is shown in the right figure. The hovering performance in the depth direction and the vertical direction is poor as compared with the horizontal direction. Furthermore, in order to confirm the dispersion in hovering for each axial direction, Figure 6 shows the average value and the standard deviation of the difference from the target position for each flight. When checking the maximum value, the average in the horizontal direction is 14 mm, the standard deviation is ± 41 mm, the average in the vertical direction is -49 mm, the standard deviation is ± 119 mm, and the average in the depth direction is -146 mm, the standard deviation is ± 155 mm. In the vertical direction, the standard deviation is large with respect to the horizontal direction. Also, in the depth direction, the dispersion of the average for each flight and the standard deviation is large with respect to the horizontal direction.

3.1.3 Discussion

We will consider the reasons for the above experiment results. Factors related to the flight performance of the UAV can be roughly divided into the following two groups.

1. Measurement performance of the UAV by vision system.
2. Control performance by the flight controller.

The difference between the horizontal direction and the depth direction of the camera is in the measurement of the UAV by the vision system. Generally, in three-dimensional measurement by the camera, the resolution of the camera depth is lower than the resolution of the camera plane.

In this system, the depth resolution is less than 1/10 of the plane. Also in the experimental result shown in FIG. 6, the average in the camera horizontal direction is 14 mm, and the average in the camera depth direction is -146 mm. Therefore, it is considered that the measurement performance of UAV by the vision system is the cause of low hovering performance in the camera depth direction

The difference between the horizontal direction and the vertical direction of the camera is controlled by a flight controller. The measurement performance of the UAV by the vision system is the same resolution in both the horizontal direction and the vertical direction of the camera. In the flight controller, when the control amount of the UAV by the vision system is small, it is automatically controlled so that the height is maintained using the barometer only in the vertical direction. In order to confirm this control performance, the output data of the barometer was confirmed. Figure 7 shows the data converted from the output data of the barometer to the height difference (vertical axis) in time series (horizontal axis). The standard deviation of the data is about ± 200 mm, which shows that the dispersion is large. Also, unlike the horizontal direction, the vertical direction is influenced by gravity, which makes control difficult. Therefore, low hovering performance in the vertical direction is considered to be due to the control performance by flight controller.

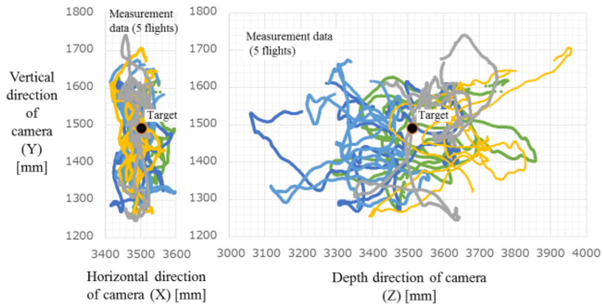

Figure 5. Locus of hovering

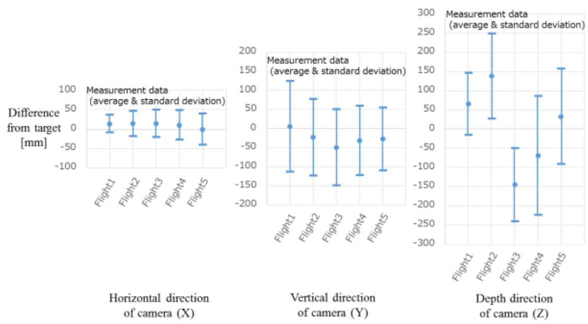

Figure 6. Difference between measurement data and target point in hovering

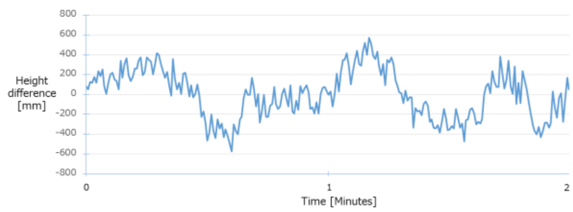

Figure 7. Height difference calculated from the measurement data of the barometer

3.2 Performance Required for Air Volume Measurement

In order to accurately measure the air volume, it is necessary to accurately approach the UAV to the diffuser so that the diffuser enters the “Collect Wind Hood”. Therefore, the approach accuracy to the diffuser by the UAV was evaluated.

Also, for accurate air volume measurement, it is necessary to collect all the conditioned air blown out from the diffuser with the “Collect Wind Hood”, so the ceiling and “Collect Wind Hood” must be in close touch with each other. According to the conventional method, a person is pushing the “Collect Wind Hood” against the ceiling, and the air volume is measured while maintaining that state. In order to check whether the state of touch with the ceiling of the UAV is about the same as the conventional method, the air volume was measured and evaluated.

3.2.1 Approach Performance

In the experiment, the target position and the position to pass through were set, the flight was made to fly from the floor surface to the diffuser, and the flight trajectory was measured five times. Approach to the target position was carried out after 25 seconds from the start of flight.

The flight trajectory is shown in Figure 8, and the difference from the target position of the approach is shown in Figure 9. In Figure 8, the vertical axis is the vertical direction of the camera (Y), the horizontal axis is the horizontal direction of the camera (X) in the left figure, and the depth direction of the camera (Z) is shown in the right figure. The flight trajectory shows that the dispersion in the depth direction is large like the hovering performance confirmed by the basic performance. As for approach accuracy, the average is 25 mm, the standard deviation is ± 15 mm in the horizontal direction of the camera, the average is 7 mm, and the standard deviation is ± 263 mm in the depth direction of the camera, which shows that the dispersion in the depth direction of the camera is large. As discussed in the evaluation of basic performance, we consider that the cause of large dispersion in the depth direction of the camera is the measurement performance of the UAV by the vision system with one camera.

To improve approach accuracy, it is necessary to construct a vision system by using two cameras. The position of the UAV in the vertical direction and the horizontal direction of the camera is measured with one camera. Furthermore, another camera is installed by changing the position of 90 ° around the UAV from the already installed camera. Then, the horizontal position of the UAV (the position in the depth direction of the other camera) is measured with the camera. By adopting the above method, the position of the UAV can be obtained without being affected by the resolution of the vision system in the depth direction of the camera, and the accuracy required for approach to the diffuser can be ensured.

3.2.2 Touch Performance

In the experiment, we measured the air volume when the UAV pressed the “Collect Wind Hood” against the ceiling. As a conventional method, the person pressed the “Collect Wind Hood” against the ceiling, the air volume was measured, and the data was compared with the data measured by the UAV. In the air volume measurement, the wind speed was measured 5 times at intervals of 1 second, the average wind speed was calculated, and the air volume was calculated. The measurement accuracy of the wind speed sensor is 5% of the measured data.

Table 2 shows the result of performing air volume measurement three times for both the conventional method and the UAV. Compared with the conventional method, it was confirmed that the measurement result using UAV is within the measurement accuracy of the wind speed sensor. From this fact, we confirmed that touch with the ceiling of the UAV is comparable to the conventional method.

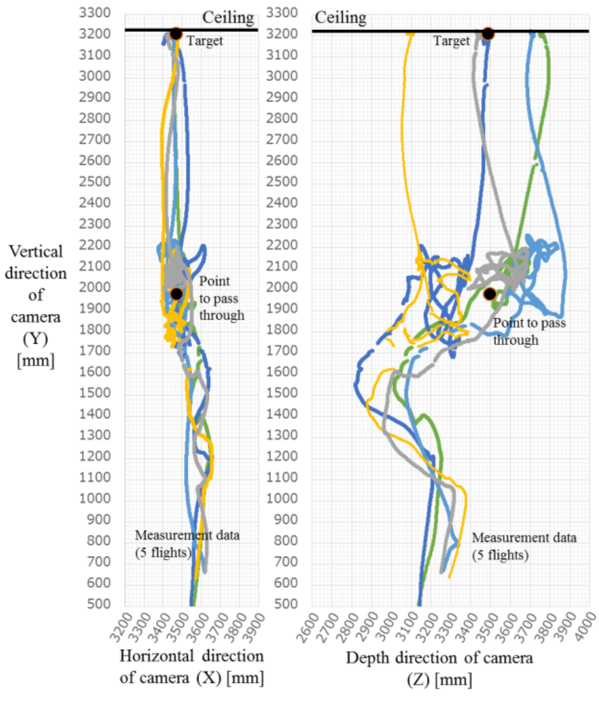

Figure 8. Locus of flight

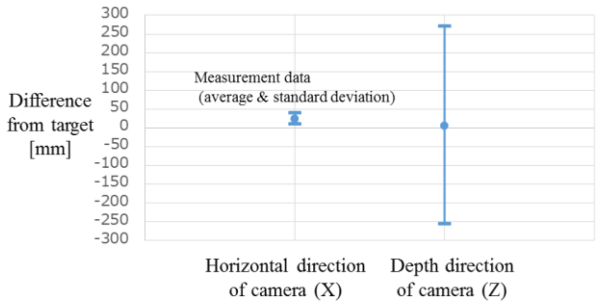

Figure 9. Difference between measurement data and target point in approach position

Table 2. Result of air volume measurement

		Measurement data [m^3/h]	Average [m^3/h]
Conventional method	No.1	380	363
	No.2	363	
	No.3	346	
UAV	No.1	371	358
	No.2	350	
	No.3	354	

4 Conclusion

For the purpose of developing UAV for use in indoor building equipment works, we made a prototype UAV capable of measuring air volume and evaluated it. As a result, the approach accuracy to the diffuser is 25 mm on average in the camera horizontal direction and ± 15 mm in standard deviation. From this, by constructing a vision system using two cameras, it was found that the accuracy required for the approach can be ensured at this experimental site. Also, from the results of the air volume measurement, it was confirmed that touch with the ceiling of the UAV was about the same as the conventional method.

In the future, in order to improve the approach accuracy to the diffuser, we will construct a vision system using two cameras and evaluate the flight performance.

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